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DOSE ASSESSMENT AT BIKINI ATOLL

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DOSE ASSESSMENT AT BIKINI ATOLL

Abstract

Bikini Atoll is one of two sites in the northern Marshall Islands that was used by the United States as testing grounds for the nuclear weapons program from 1946 to 1958. In 1969 a general cleanup began at Bikini Atoll. Subsistence crops, coconut and Pandanus fruit, were planted on Bikini and Eneu Islands, and housing was constructed on Bikini Island.

A second phase of housing was planned for the interior of Bikini Island. Preliminary data indicated that external gamma doses in the interior of the island might be higher than in other parts of the island. Therefore, to select a second site for housing on the island with minimimum external exposure, a survey of Bikini Atoll was conducted in June 1975. External gamma measurements were made on Bikini and Eneu Islands, and soil and vegetations samples collected to evaluate the potential doses via terrestrial food chains and inhalation. Estimates of potential dose via the marine food chain were based upon data collected on previous trips to the atoll.

Six living patterns were evaluated. One was based on living and obtaining all subsistence crops from Bikini Island, another on living on and obtaining all subsistence crops from Eneu Island. Other patterns consisted of various combinations of housing and subsistence crops from the two islands.

The terrestrial pathway contributes the greater percentage, external gamma exposure contributes the next highest, and inhalation and marine pathways contribute minor fractions of the total whole body and bone marrow doses. The radionuclides contributing the major fraction of the dose are ^{90}Sr and ^{137}Cs.

All living patterns involving Bikini Island exceed federal guidelines for 30-yr population doses. The Eneu Island living pattern leads to doses that are slightly less than federal guidelines. All patterns evaluated for Bikini Atoll lead to higher doses than those on the southern islands at Enewetak Atoll.

Purpose of the 1975 Bikini Survey

Bikini Atoll is one of two sites in the northern Marshall Islands that were used by the United States as testing grounds for the nuclear weapons

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program from 1946 to 1958. The Bikini people, since their initial relocation to Rongerik Atoll in 1946, have had a continuing desire to return to their homeland; so in the latter part of the 1960's, the first steps toward rehabitation of Bikini Atoll were taken. In 1969 a general cleanup of debris and buildings began at Bikini Atoll. Concurrently, scrub vegetation was cleared from Bikini and Eneu Islands, the two major residential islands of the Bikini people prior to their relocation (see Fig. 1). An agricultural reclamation program was initiated with the planting of coconut trees on Eneu and Bikini. Additional subsistence crops of breadfruit, Pandanus fruit, papaya, and banana were planted on Bikini Island.

To facilitate resettlement, 43 houses were constructed on Bikini Island between 1969 and 1974. A second phase of housing was planned for the interior of Bikini Island; however, preliminary data indicated that the external gamma dose in the interior of Bikini Island might be higher than in other parts of the island. Therefore, to select a site for the location of second phase housing at Bikini Island that would

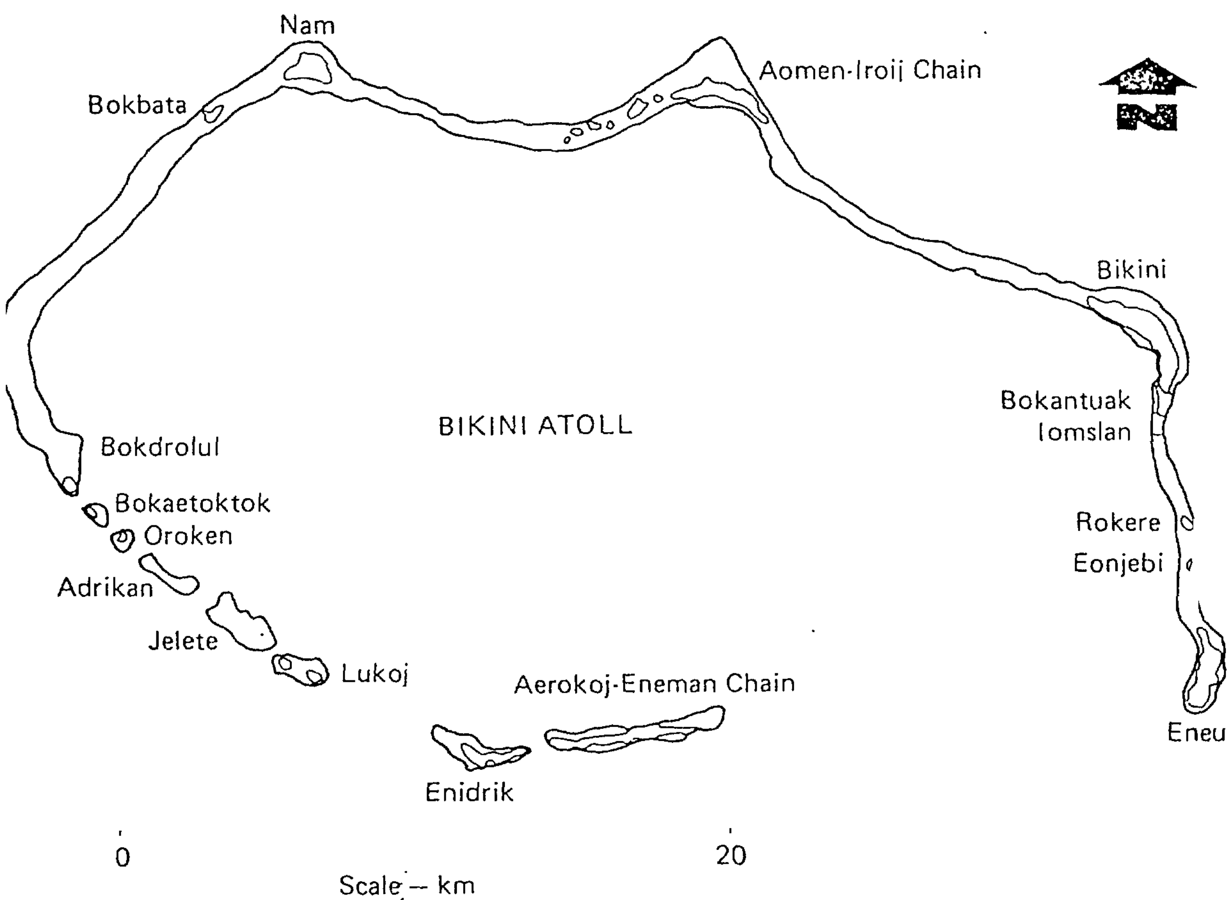

Fig. 1. Map of Bikini Atoll.

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minimize external exposure, a survey of Bikini Atoll was proposed. Initial plans called for aerial surveys to determine external gamma levels on all islands in the atoll along with ground surveys using scintillation counters and thermoluminescent dosimeters (TLD). Emphasis was to be placed on Bikini and Eneu Islands, the prime residence islands. In addition, there was to be a rather large scale effort to sample the soil and vegetation to evaluate the potential dose via the terrestrial pathway. It was felt that this was an especially important goal in view of the significance of the contribution of the food chain to the total dose estimated at Enewetak Atoll.[1]

For a number of reasons, the scale of the program had to be reduced from that originally planned. Manpower and support were reduced, and the aerial survey was temporally deferred, leaving the entire program of measuring the external dose levels on Bikini and Eneu Islands to be accomplished by ground crews.[2] The emphasis of this reduced effort was toward the external gamma measurements on Bikini and Eneu Islands. Although the sampling of the food chain pathways was less extensive than we had hoped, we maintained a smaller scale program designed to help assess the potential dose via ingestion pathways. The 1975 Bikini survey was conducted with the help of 20 people (see acknowledgment) and the support of the ERDA Research Vessel, Liktanur, from June 16 through June 24, 1975.

The basic plans for the 1975 Bikini survey are outlined below.

SURVEY PROGRAM OF BIKINI SOIL AND GAMMA EXPOSURE RATE

Survey of Gamma-Exposure Rate

The program for the measurement of gamma-ray exposure rates conducted on the ground was designed to examine in detail the geographical variability of the exposure rates on Bikini and Eneu Islands, and verify exposure-rates measured during previous visits.

Methods and Measurements

A Baird-Atomic scintillation detector, which consists of a 2.5-cm-diam × 3.9-cm-long NaI crystal with a ratemeter readout was used. The instrument was calibrated with a ^{137}Cs point source in the primary calibration range of the National Environmental Research Center, Las Vegas, Nevada. While the response of this instrument is energy-dependent, our experience at Enewetak showed that this was not a serious limitation because of the dominance of ^{137}Cs in the radiation background on the atoll. We also used a Reuter-Stokes high pressure ionization chamber. The current produced by the radiation-induced ionization within the chamber is measured by a sensitive

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electrometer with a digital readout. The instrument exhibits a flat energy response over all gamma-ray energies of interest to this survey. It is capable of measuring exposure rates from approximately 1 to 200 μR/hr with an accuracy of about 5%. Thus, the data from this instrument were used as a reference for measurements by other techniques.

Exposure rates at 1 m above the ground were measured with the NaI scintillator at approximately 2500 locations on a 30-m rectangular grid on Bikini Island and at about 120 locations on a 120-m grid on Eneu Island. The ionization chamber was primarily used for measurements within the central section of Bikini Island with additional measurements made at selected areas. Thus, from this program a very comprehensive picture of the gamma-ray exposure rates at both islands is available. Thermoluminescent dosimeters (TLDs) provided a third technique for evaluating the external dose. A complete report on the external gamma measurements and resulting dose assessment has been published.[2]

Soil Survey

The soil sampling program was designed to identify the primary radionuclides contributing to the external gamma exposure and to determine the geographical distribution of these radionuclides in the soil on Bikini and Eneu Islands of the Bikini Atoll. This sampling program was integrated with previous programs to avoid duplication of effort. The actual number of samples taken and their specific collection sites were determined by expected activity levels, home-construction plans, agricultural plans, and the number of locations of recent soil samples collected by other programs.

Methods and Measurements

Two types of soil samples were collected for analysis: a 15-cm deep, surface-core sample of 60-cm^2 area, and a profile collection based upon sidewall sampling in a trench in which samples of 100-cm^2 area were collected at 15-cm-depth increments to a depth of 90 cm. To plan the survey, Bikini Island was divided into the north, central, and south sections along the respective second baseline roads. Eneu was divided by the airstrip into the north and south sections. The approximate numbers of surface and profile samples collected within these sections are given in Table 1.

Note that a major fraction of the surface samples were collected within the central section of Bikini Island. This was because of the higher and more variable gamma-exposure rates in this area and the fact that a major fraction of the returning Bikinians are likely

Table 1. Distribution of soil sample locations on Bikini and Eneu Islands.

	No. of sample locations	
	Surface (0-15 cm)	Profiles (0-90 cm)
Bikini		
North of second baseline N	25	2
Central section	200	4
South of second baseline S	25	2
Eneu		
North of airstrip	60	2
South of airstrip	40	2
Total	350	12[a]

[a]6 samples each.

to live in this section. A limited number of profile samples were planned in this area because several samples were collected during previous surveys. The north and south sections of Bikini Island and all of Eneu have lower contamination levels; hence, the sampling density was lower. Special emphasis, however, was given to the lagoon side of both islands since homes may also be erected in these areas.

The exact soil-sampling locations were determined by a random selection process to obtain statistically meaningful and unbiased results. Special samples were also collected within "hot spot" areas and other areas of special interest. The samples were placed in plastic bags with identification tags and prepared for shipment to LLL where they were processed and analyzed by gamma spectroscopy. Samples were analyzed for $^{239,240}Pu$ and ^{90}Sr by wet chemistry methods at McClellan Laboratory. A complete report on the analytical procedures has been published.[3]

BIKINI GROUND WATER PROGRAM

Purpose

The ground water program was designed to establish a network of well locations on Bikini and Eneu Islands to assess the ground water quality and to study systematically the hydrology and geochemistry of radionuclides and major and trace elements in the ground water system. Water movement and residence times were to be assessed to deduce the transport rates and mechanisms of radionuclides deposited in the soil zone or taken up by vegetation.

Methods and Measurements

Pits were dug with a backhoe to the hard coral layer; the ground water reservoir surface was approximately 2 m below the ground surface. Seven holes were drilled with a ground power auger at selected locations along the centerlines of Bikini and Eneu Islands. The auger penetrated the ground water lens to a depth of approximately 1 to

1.5 m. Each hole was cased with slotted 2-in-diameter polyvinylcarbonate pipe that was extended to the soil surface. The pits were backfilled to minimize impact on the environment.

The first hole was located near the island center. The salinity of the water was measured with an *in situ* conductivity probe. Two holes were then drilled on opposite sides of the center hole and the salinity measured in each. Water was pumped from the wells, filtered, and sampled. Radionuclides, major elements, nutrients, and bacteria were measured at the Lawrence Livermore Laboratory to provide data for water quality. Specific wells were pumped continuously during a day and sampled serially to determine changes in water quality as a function of usage.

The well network is available for resampling. On subsequent trips to the atoll we plan to assess thoroughly the dynamics of radionuclide cycling in the ground water reservoir and to maintain a surveillance of the water quality. The program operation was fashioned after our Enewetak ground water study, and comparison of the data from both atolls should be especially valuable for predicting the mechanism and rates of cycling of the constituents in ground water at Pacific atolls. A complete report on the Bikini and Eneu ground water sampling and analysis has been published.[4]

PLANT/SOIL SAMPLING PROGRAM

Purpose:

The main thrust of the program was to determine radionuclide concentrations in food species, to correlate these with soil concentrations at various depths, to determine nuclide availability to plants in the coral soils, and to relate the radioactivity in food species to that in indigenous nonfood species that have the potential to serve as indicator species. The unique information that this survey provided is:

- Soil-to-plant and soil-to-fruit concentration factors for detectable radionuclides,
- The relationship between food species and nonfood species at the same location,
- Intra-island variability in radionuclide concentration in the vegetation, and
- A data base for assessment of terrestrial food chain transfer of radioactivity from the soil to man for long-term dose evaluation following resettlement of the atoll.

Methods and Measurements

The sampling program consisted of the integration of a series of samples of food species with soil profile samples obtained on an *ad hoc*, available species basis. All food species growing and bearing fruit on Bikini were sampled. A broader sampling program based upon the widely available natural species, *Messerschmidia* and *Scaevola*, was also carried out to determine the intra-island variations in the radioactivity of the vegetation. Soil profiles were obtained from the root zone of each tree that was sampled to determine the concentration of radioactivity in the root-soil environment. Both leaves and fruit were sampled so that leaf-to-fruit concentration ratios could be calculated. Nonfood species were sampled in the vicinity of food species to provide information on species variation in radionuclide uptake and to evaluate the use of concentrations in nonfood species when no food products are available for analysis to predict the impact of human intake. This approach was developed in the Enewetak survey because of the paucity of food species on the atoll. The soil sampling results and the concentration and correlation factors developed from the plant-soil data have been published as a separate report.[5]

This program along with the ground water program supplies the data base for assessing the long-term dose commitment via food chains and rehabitation of the atoll.

BIKINI AIR SAMPLING AND RESUSPENSION MEASUREMENT PROGRAM

Because of limited support facilities, manpower, and time and because of other program demands for air sampling equipment resulting from delays in fielding the Bikini survey, no attempt was made to establish an air sampling program during this survey.

SAMPLE PROCESSING

Upon completion of the field survey in June, nearly 1000 samples including soil, vegetation, animals, and water were returned to LLL for processing and analysis. Because of funding problems, the processing of the samples was not begun until late September; processing was completed by early November 1975. Sample processing is discussed in detail in Ref. 3. The time required to analyze these samples was considerable and was incorporated into a priority framework involving other programs. In addition, funding problems prevented analysis of all samples, so time was required to establish priorities for samples that were sent for analysis. As data became available and as assessment activities began, additional samples that were of particular importance for assessment purposes were identified. When limited additional funding became available in the summer of 1976, second priority samples were sent for analysis and incorporated into our assessment. Our data bank for the samples that were analyzed was completed in October 1976.

REPORTING OF RESULTS

The results of this survey are presented in a series of reports, each dealing with a specific area. The reports covering the 1975 Bikini Survey are:

- P. H. Gudiksen, T. R. Crites, and W. L. Robison, *External Dose Estimates for Future Bikini Atoll Inhabitants*, Lawrence Livermore Laboratory, Rept. UCRL-51879 Rev. 1 (1976).
- M. E. Mount, W. L. Robison, S. E. Thompson, K. O. Hamby, A. L. Prindle, and H. B. Levy, *Analytical Program: 1975 Bikini Radiological Survey*, Lawrence Livermore Laboratory, Rept. UCRL-51879, Part 2 (1976).
- C. S. Colsher, W. L. Robison, and P. H. Gudiksen, *Evaluation of the Radionuclide Concentrations in Soil and Plants from the 1975 Terrestrial Survey of Bikini and Eneu Islands*, Lawrence Livemore Laboratory, Rept. UCRL-51879, Part 3 (1977).
- V. E. Noshkin, W. L. Robison, K. M. Wong, and R. J. Eagle, *Evaluation of Radiological Quality of the Water on Bikini and Eneu Islands in 1975: Dose Assessment Based on Initial Sampling*, Lawrence Livermore Laboratory, Rept. UCRL-51879, Part 4 (1977).
- W. L. Robison, W. A. Phillips, and C. S. Colsher, *Dose Assessment of Bikini Atoll*, Lawrence Livermore Laboratory, Rept. UCRL-51879, Part 5 (1977).
- W. L. Robison and W. A. Phillips, *Annual Doses and Body Burdens Predicted for Bikini and Eneu Islands*, Lawrence Livermore Laboratory, Rept. UCRL-51879, Part 6 (in preparation).

Living Patterns and Diet

Bikini and Eneu Islands were the two major islands at Bikini Atoll used for residence prior to the evacuation of the Bikini people in 1947. The living patterns adopted for assessment in this report reflect this history and the continuing desire of the people to use these two islands for residence. Since subsistence agriculture will of course occur on the residence islands, our assessments evaluate both external and ingestion pathways. The possible living patterns that we assessed are listed in Table 2. These living patterns cover a range of possible exposures that could be incurred by a sizeable portion of the returning Bikini population and are the composite of information obtained from the Bikini people, Trust Territory personnel, and studies conducted in support of the Radiological Survey.[3]

Table 2. Assumed living patterns

Pattern	Description
1	No use of Bikini Island at present as housing or food production areas. Eneu Island for housing and food production. Unrestricted use of fish throughout the atoll.
2	Residence on Bikini Island limited to houses already constructed. No additional house construction for the present. Use of coconuts grown on Bikini Island. Other food crops grown on Eneu Island only. Unrestricted use of fish from all parts of the atoll. Bikini Island groundwater for agriculture only.
3	Limited use of Bikini Island with the following remedial actions by (a) placing 5 cm of clean coral gravel around existing houses to a distance of 10 m, and (b) removal of the top 20 cm of soil and replacement with clean soil to a distance of 10 m from the houses. All food grown on Bikini Island are acceptable except Pandanus and breadfruit. Unrestricted use of fish throughout the atoll. Use of Bikini Island groundwater for agriculture only.
4	Limited use of Bikini Island with Phase II houses constructed only along the lagoon road within Area 2 of Fig. 2. Remedial actions of Pattern 3 taken. Use of coconuts grown on Bikini Island but not Pandanus and breadfruit. Unrestricted use of fish through the atoll.
5	Plase II housing construction according to the Preliminary Bikini Atoll Master Plan, but no use of Pandanus and breadfruit from Bikini Island. Unrestricted use of fish throughout the atoll. Groundwater for agriculture and washing only.
6	Phase II housing constructed according to the Preliminary Bikini Atoll Master Plan. All foods grown on Bikini Island are acceptable. Unrestricted use of fish throughout the atoll. Groundwater used for agriculture and washing only.

In addition to living patterns, another major factor in determining the potential dose to the returning population is the diet. A considerable effort was made in the 1972 Enewetak Survey[6] to predict the diet of the returning Enewetak population. Based upon those efforts and discussions with the Bikini people, Trust Territory personnel, and our observation of the few families presently living on Bikini Island, the diets listed in Table 3 should reflect a reasonable estimate of the diet of the returning population.

Two diets are listed: One for 1975 and another for 1980. The difference in the diets reflects our estimates of the availability of certain food products. For example, on Bikini most of the coconut trees are presently not bearing fruit, and for the most part coconut fruit availability will be limited throughout the next 5 years. By 1980, however, sufficient coconut will be available so that there should be no such limitations on dietary intake of coconut. Similarly, Pandanus and breadfruit are not fully matured on Bikini Island; and since it will be a few years before these plants are very productive, only a few fruit are occasionally available. Once again, by 1980 the availability of both Pandanus and breadfruit should be sufficient for normal subsistence use and could be included in the diet if radionuclide levels are not excessive. Presently on Eneu Island there are no Pandanus fruit or breadfruit; however, coconuts are available. By 1980 availability of coconut milk and meat should not be limiting. We have also assumed that both Pandanus fruit and breadfruit will be available by 1980 on Eneu.

These dietary estimates are similar to those in the assessment of Enewetak Atoll[6] and are based upon the research conducted at that time, which included discussions with and observations of the Enewetak people living on Ujilang and information from Dr. Jack Tobin, an anthropologist and then resident of the Marshall Islands, and Dr. Mary Murai of the University of California School of Public Health, who lived in the Marshall Islands for several years and has published a book on the Marshallese diet.[7] In addition, we have since had the opportunity to observe first hand how both the Enewetak and the Bikini people take advantage of the available marine and terrestrial resources.

The use of imported foods will surely continue to varying degrees. To the extent that these imports may reduce the daily intake of locally grown food products or locally available marine resources will in turn reduce the dose estimates in this report since these estimates are based upon the diets listed in Table 3. The diet should be evaluated after the people return to determine the extent to which it deviates from the diet used in this dose assessment.

Table 3. Estimated diet for Bikini and Eneu Islands.

	Intake (g/da)		
	1975		1980
Food item	Bikini	Eneu	Bikini and Eneu
Fish	600	600	600
Domestic meat	100	100	100
Pandanus fruit	50	—	200
Breadfruit	50	—	150
Wild birds	20	20	20
Bird eggs	10	10	10
Coconut meat	100	100	100
Coconut milk	100	100	300
Coconut crab	25	25	25
Clams	25	25	25
Garden vegetables	50	50	50
Total	1130	1030	1580
			plus imports

Methods of Dose Calculation

The external dose measurements and calculations from gamma-emitting radionuclides, primarily ^{137}Cs and ^{60}Co, distributed in the soil on Bikini and Eneu Islands has been described in detail.[2]

Previous studies of the aged fallout[1,8] in the Marshall Islands and the analytical data reported here indicate that only ^{60}Co, ^{90}Sr, ^{137}Cs, ^{241}Am, and plutonium isotopes contribute to the internal dose. The doses resulting from the inhalation and ingestion of these nuclides have been calculated using the most recent models, transfer coefficients, and turnover times available. The dose from ^{60}Co was based upon a single-exponential model with a biological half time of 10 da.[9] The transfer across the gut to whole body was taken as 0.3. For ^{137}Cs a two-component exponential function was used. All of the ^{137}Cs ingested is assumed to reach the whole body. Of the total ^{137}Cs reaching the body, 15% has a biological half time of 1 da and 85% has a biological half time of 115 days.[10]

The critical organ for ^{90}Sr-dose calculation is bone marrow. The doses from ^{90}Sr in this report are given for bone marrow and are calculated by the method developed by Spiers[11-13] and used in the UNSCEAR reports.[14] This model calculates the dose with a quality factor (QF) of 1 without the use of an *n* factor for nonuniform distribution in the bone.[15] Under these conditions the bone marrow doses should be compared to the 0.5 rem/yr guideline for members of the public rather than the 3 rem/yr criteria[16-18] used if mineral bone doses are calculated using an *n* factor of 5.[9,15] The bone liver doses of $^{239,240}Pu$ were calculated using the ICRP lung model[19,20] and the most recent parameters for transfer from the lung, across the gut wall, and for retention time in the critical organs.[19,21] A summary description of this model and associated transfer and retention coefficients is given in a recent paper by Martin and Bloom.[22]

Table 4. Disintegration energy (E) and fractional deposition (F) in reference organ of five major radionuclides.

Radionuclide	E, MeV	Bone F^a	Liver F	Whole Body F
^{137}Cs	0.59	—	—	1.0
^{90}Sr	1.1	0.3	—	—
^{60}Co	0.87	—	—	0.3
$^{239,240}Pu$	53	1.35(-5)	1.20(-5)	—

[a]Numbers in parentheses indicate powers of 10, i.e., (-5) indicates $\times 10^{-5}$.

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The effective energies (E) and the fraction of ingested nuclide reaching the reference organ (F) of the four radionuclides that produce over 99% of the dose are listed in Table 4.

Exposure Pathways: Description and Dose

EXTERNAL GAMMA DOSE

The description of the measurements, dose calculations, and dose estimates for the external exposure pathway have been reported in detail.[2] In summary, ^{137}Cs and ^{60}Co produce nearly all the external dose on both Bikini and Eneu Islands, with ^{137}Cs contributing approximately 94% of the total. In addition, the dose levels on Eneu Island were about one-half those on Bikini Island.

The first-yr dose and 30-yr integral dose on the two islands as a function of the alternative living patterns is shown in Table 5. Integrated external exposures for 10, 30, 50, and 70 yr are listed in Tables 6 through 9, respectively. Residence in the interior of Bikini Island (Fig. 2, Area 3) gives the highest external exposure (Patterns 5 and 6). The annual Federal guideline for a member of the population recommends a dose less than 0.5 rem for the whole body and 0.5 rem for bone marrow.[23-26] For Patterns 5 and 6 the estimated first-yr dose of 0.25 rem (excluding natural background) is a significant fraction of the amount recommended by the annual guideline and leaves little room for dose accumulation via other pathways. Similarly, the annual guidelines for a population for 30 yr is 5 rem, and the estimated 30-yr integral dose (excluding natural background) for Patterns 5 and 6 is 5.1 rem. Again, over a 30-yr period, the external dose received from this housing location and living pattern allows no contribution by exposure from other pathways. This is very significant because potential doses via the terrestrial food chain can exceed those resulting from external exposure.

Housing constructed in Area 2 (Table 2, Patterns 4a and 4b) along the lagoon road reduces the external exposure relative to Patterns 5 and 6 by approximately 25%, depending upon which remedial action is considered. Commonly, crushed gravel is placed around the houses and is accomplished easily. Soil removal and replacement, however, are more difficult to implement. Living in residences already established on Bikini Island (Fig. 3; in Fig. 2, Area 1) gives the smallest external exposure on Bikini Island

Table 5. Estimated integral whole-body, external gamma doses for the first yr and for 30 yr. Values include contributions resulting from natural background radiation of about 0.027 rem for a first-yr dose and 0.80 rem for a 30-yr dose. For comparison, the Federal radiation guideline (total of external and internal doses) is 0.5 rem/yr for individuals and 5 rem for 30 yr for a population average. These guidelines are in addition to natural background.

Pattern[a]	Description	Estimated doses (rem) First yr	Estimated doses (rem) 30 yr
1	Village on Eneu Island.	0.12	2.9
2	Residence in houses already constructed along lagoon road on Bikini Island.	0.20	4.3
3	Residence in houses already constructed along lagoon road on Bikini Island with the following remedial actions taken:		
	a. Placing 5 cm of gravel around houses,	0.18[b]	4.1[b]
	b. Removing and replacing top 20 cm of soil around houses.	0.18[b]	4.0[b]
4	Residence in Phase II houses constructed along lagoon road within Area 2 of Fig. 2 with the following remedial actions taken:		
	a. Placing 5 cm of gravel around houses,	0.22[b]	4.8[b]
	b. Removing and replacing top 20 cm of soil around houses.	0.20[b]	4.4[b]
5	Residence in Phase II houses constructed within the interior of Bikini Island.	0.28	5.9
6	Residence in Phase II houses constructed within the interior of Bikini Island.	0.28	5.9

[a]See Table 2.

[b]The exposure rates in the immediate vicinity of the houses have been reduced by a factor of two and eight for remedial actions a and b, respectively. However, we have estimated that only 35 to 40% of the Bikinian's time will be spent in the vicinity of his house; therefore, the reduction in total dose is relatively small because the total dose includes the exposure received from the areas where he spends the remainder of his time.

(Patterns 2, 3a, and 3b); the 30-yr doses (excluding natural background) for these patterns range from 3.2 to 3.5 rem. Living patterns on Eneu Island lead to the lowest external exposure doses. The first-yr dose of 0.093 rem and the integrated 30-yr dose of 2.1 rem are nearly one-half

Table 6. Integral 10-yr dose, rem.

Living pattern	Inhalation: Lung	Inhalation: Bone	Inhalation: Liver	External[a]: WB,[b] bone marrow, liver	Marine: WB[b]	Marine: Bone marrow	Marine: Liver	Terrestrial: WB[b]	Terrestrial: Bone marrow	Terrestrial: Liver	Water: WB[b]	Water: Bone marrow	Water: Liver	Total: WB[b]	Total: Bone marrow
1	6.8(-3)[c]	5.7(-4)	4.5(-4)	0.87	2.3(-2)	7.4(-2)	2.3(-2)	0.67	1.0	0.67	1.2(-2)	7.7(-2)	1.2(-2)	1.5	2.0
2	4.6(-2)	3.9(-3)	3.1(-3)	1.5	2.3(-2)	7.4(-2)	2.3(-2)	4.2	4.9	4.2	7.5(-4)	3.8(-3)	7.5(-4)	5.7	6.4
3	4.6(-2)	3.9(-3)	3.1(-3)	1.4	2.3(-2)	7.4(-2)	2.3(-2)	5.1	6.4	5.1	7.5(-4)	3.8(-3)	7.5(-4)	6.5	7.8
4	4.6(-2)	3.9(-3)	3.1(-3)	1.7	2.3(-2)	7.4(-2)	2.3(-2)	4.2	4.9	4.2	7.5(-4)	3.8(-3)	7.5(-4)	5.1	6.7
5	4.6(-2)	3.9(-3)	3.1(-3)	2.1	2.3(-2)	7.4(-2)	2.3(-2)	5.1	6.4	5.1	7.5(-4)	3.8(03)	7.5(-4)	7.2	8.5
6	4.6(-2)	3.9(-3)	3.1(-3)	2.1	2.3(-2)	7.4(-2)	2.3(-2)	7.6	11	7.6	7.5(-4)	3.8(-3)	7.5(-4)	9.7	14

[a]Natural background subtracted.

[b]WB = whole body.

[c]Numbers in parentheses indicate powers of 10, i.e., (-3) indicates $\times 10^{-3}$.

Table 7. Integral 30-yr dose, rem.

Living pattern	Inhalation: Lung	Inhalation: Bone	Inhalation: Liver	External[a]: WB,[b] bone marrow, liver	Marine: WB[b]	Marine: Bone marrow	Marine: Liver	Terrestrial: WB[b]	Terrestrial: Bone marrow	Terrestrial: Liver	Water: WB[b]	Water: Bone marrow	Water: Liver	Total: WB[b]	Total: Bone marrow
1	2.4(-2)[c]	7.8(-3)	5.8(-3)	2.1	5.0(-2)	0.20	5.3(-2)	2.0	3.3	2.0	2.9(-2)	2.2(-1)	2.9(-2)	4.2	5.8
2	0.16	5.3(-2)	3.9(-2)	3.5	5.0(-2)	0.20	5.3(-2)	12	15	12	1.9(-3)	1.1(-2)	1.9(-3)	16	18
3	0.16	5.3(-2)	3.9(-2)	3.3	5.0(-2)	0.20	5.3(-2)	14	18	14	1.9(-3)	1.1(-2)	1.9(-3)	18	22
4	0.16	5.3(-2)	3.9(-2)	4.0	5.0(-2)	0.20	5.3(-2)	12	15	12	1.9(-3)	1.1(-2)	1.9(-3)	16	19
5	0.16	5.3(-2)	3.9(-2)	5.1	5.0(-2)	0.20	5.3(-2)	14	18	14	1.9(-3)	1.1(-2)	1.9(-3)	19	24
6	0.16	5.3(-2)	3.9(-2)	5.1	5.0(-2)	0.20	5.3(-2)	23	37	23	1.9(-3)	1.1(-2)	1.9(-3)	28	42

[a]Natural background subtracted.

[b]WB = whole body.

[c]Numbers in parentheses indicate powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

Table 8. Integral 50-yr dose, rem.

Living pattern	Inhalation: Lung	Inhalation: Bone	Inhalation: Liver	External[a]: WB,[b] bone marrow, liver	Marine: WB[b]	Marine: Bone marrow	Marine: Liver	Terrestrial: WB[b]	Terrestrial: Bone marrow	Terrestrial: Liver	Water: WB[b]	Water: Bone marrow	Water: Liver	Total: WB[b]	Total: Bone marrow
1	4.1(-2)[c]	2.3(-2)	1.6(-2)	2.9	6.6(-2)	0.29	7.4(-2)	2.8	4.7	2.8	4.0(-2)	0.32	4.0(-2)	5.8	8.2
2	0.28	0.16	0.11	4.8	6.6(-2)	0.29	7.4(-2)	17	21	17	2.6(-3)	1.6(-2)	2.7(-3)	22	26
3	0.28	0.16	0.11	4.6	6.6(-2)	0.29	7.4(-2)	20	26	20	2.6(-3)	1.6(-2)	2.7(-3)	25	31
4	0.28	0.16	0.11	5.5	6.6(-2)	0.29	7.4(-2)	17	26	20	2.6(-3)	1.6(-2)	2.7(-3)	23	27
5	0.28	0.16	0.11	5.5	6.6(-2)	0.29	7.4(-2)	17	26	20	2.6(-3)	1.6(-2)	2.7(-3)	28	32
6	0.28	0.16	0.11	7.0	6.6(-2)	0.29	7.4(-2)	33	53	33	2.6(-3)	1.6(-2)	2.7(-3)	40	61

[a]Natural background subtracted.

[b]WB = whole body.

[c]Numbers in parentheses indicate powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

Table 9. Integral 70-yr dose, rem.[6]

Living pattern	Inhalation: Lung	Inhalation: Bone	Inhalation: Liver	External[a]: WB,[b] bone marrow, liver	Marine: WB[b]	Marine: Bone marrow	Marine: Liver	Terrestrial: WB[b]	Terrestrial: Bone marrow	Terrestrial: Liver	Water: WB[b]	Water: Bone marrow	Water: Liver	Total: WB[b]	Total: Bone marrow
1	5.8(-2)[c]	4.6(-2)	3.0(-2)	3.3	7.6(-2)	0.35	9.0(-2)	3.3	6.6	3.3	4.7(-2)	3.7(-1)	4.7(-2)	4.7	11
2	0.39	0.31	0.20	5.5	7.6(-2)	0.35	9.0(-2)	21	25	21	3.0(-3)	1.9(-2)	3.2(-3)	26	31
3	0.39	0.31	0.20	5.2	7.6(-2)	0.35	9.0(-2)	24	31	24	3.0(-3)	1.9(-2)	3.2(-3)	29	36
4	0.39	0.31	0.20	6.4	7.6(-2)	0.35	9.0(-2)	21	25	21	3.0(-3)	1.9(-2)	3.2(-3)	27	32
5	0.39	0.31	0.20	8.1	7.6(-2)	0.35	9.0(-2)	24	31	24	3.0(-3)	1.9(-2)	3.2(-3)	32	39
6	0.39	0.31	0.20	8.1	7.6(-2)	0.35	9.0(-2)	39	63	39	3.0(-3)	1.9(-2)	3.2(-3)	47	72

[a]Natural background subtracted.

[b]WB = whole body.

[c]Numbers in parentheses indicate powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

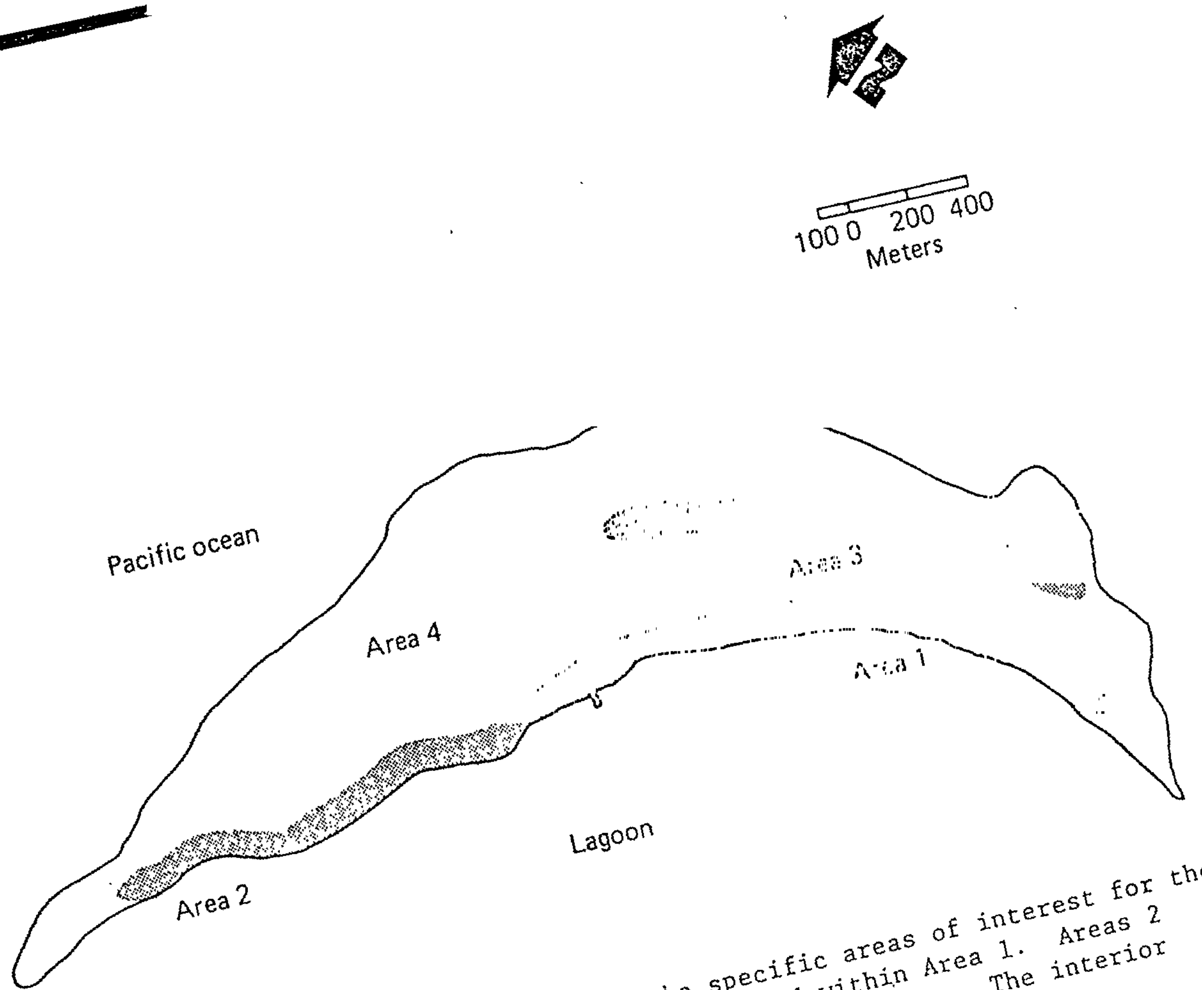

Fig. 2. A map of Bikini Island showing the specific areas of interest for the dose calculations. Existing houses are situated within Area 1. Areas 2 and 3 are proposed village sites for future housing units. The interior portion of the island is denoted by Area 4.

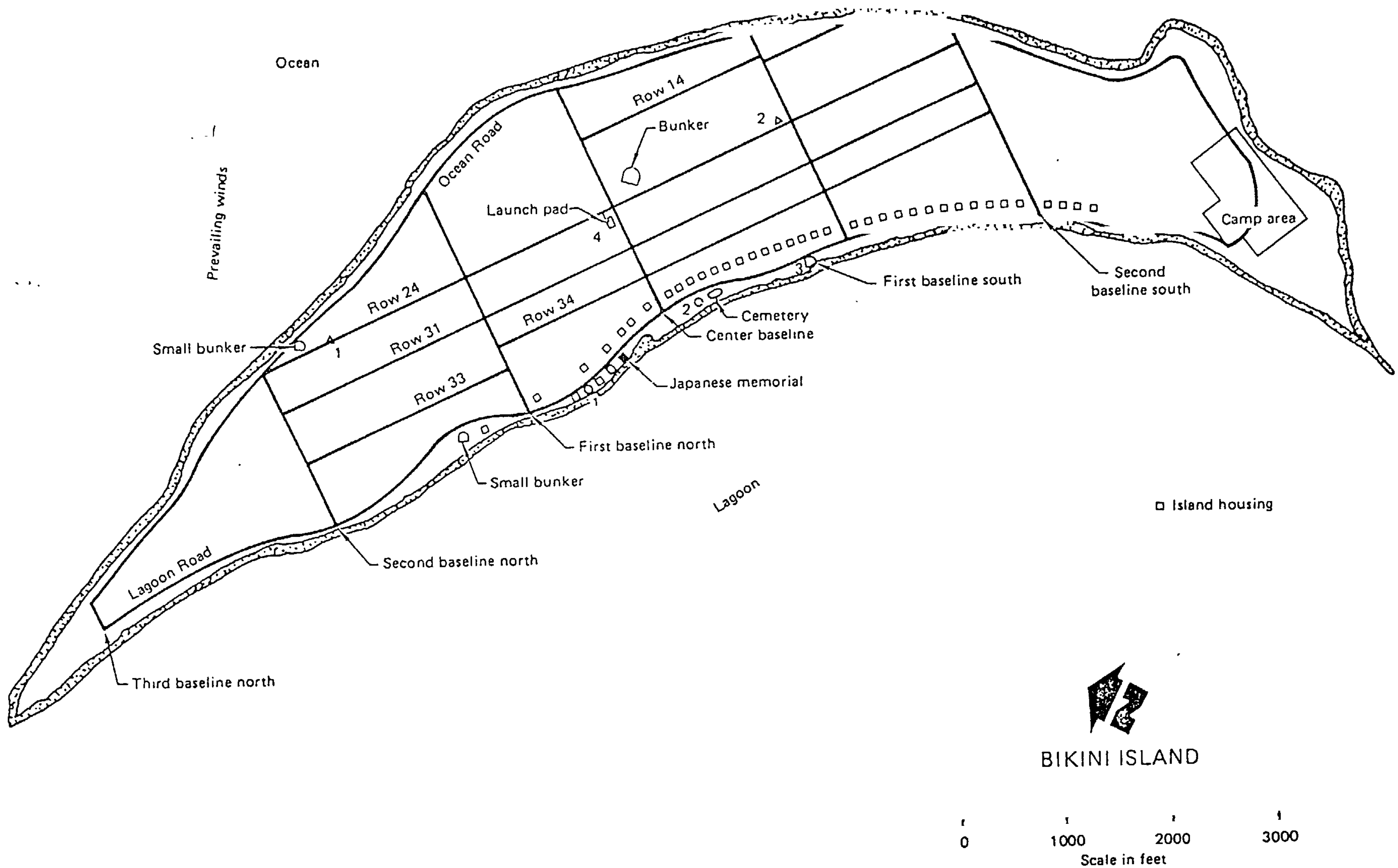

Fig. 3. Map of Bikini housing.

the Bikini Island options. The Eneu living pattern, therefore, has more flexibility for potential exposure via other pathways without exceeding Federal guidelines.

INHALATION PATHWAY

No air sampling data were taken during the 1975 Bikini survey. Open field aerosols were measured to some extent previously at Bikini Atoll.[8,27] Because of the sparsity of data, however, and also the lack of data on resuspension processes in the atoll environment, the average concentrations of Pu in the soil were used in a mass loading model to predict the doses via the inhalation pathway. This is the same approach used to evaluate the inhalation pathway at Enewetak Atoll.[28]

The mass loading concept may be more relevant for estimating the potential dose via inhalation than open air aerosol measurements because the resuspended material created by a person in his own immediate environment may be significantly greater than is reflected in open air measurements. Therefore, it is assumed that the concentration of Pu observed in the surface soil at Bikini and Eneu Islands will remain the same in the respirable, resuspended surface material. In addition, a mass loading of 100 $\mu g/m^3$ and a breathing rate of 20 m^3/da were used to develop the Pu inhalation rate in pCi/da. A mass loading of 100 $\mu g/m^3$ is at the high end of the observed range for normal open air aerosol measurements. However, since local resuspension created in the immediate vicinity of an individual during his normal activities is probably greater than open air measurements, it appears reasonable, for lack of specific data, to use the higher number. The average $^{239,240}Pu$ concentrations in the surface soils (0 to 5 cm) of Bikini and Eneu Islands are 9.3 and 1.4 pCi/g, respectively. The pCi/day intake resulting from the above model is, therefore, 0.019 for Bikini and 0.0028 for Eneu.

The doses resulting from inhalation of $^{241,240}Pu$ are listed in Table 10 for the three critical organs: lung, bone, and liver. The doses predicted on Eneu are, of course, less than those predicted on Bikini Island. These doses will be compared below with bone and whole body dose from other pathways.

Two other isotopes must be considered in the inhalation pathway — ^{241}Pu and ^{241}Am. The concentration of ^{241}Pu in the soil on Bikini and Eneu is approximately 10 times that of $^{239,240}Pu$.[3] However, because of low energy beta radiation (0.021 MeV maximum) and a much shorter half life (14 yr) the integrated 30-, 50-, and 70-yr doses from ^{241}Pu are more than one-tenth less than those listed in Table 10 for $^{239,240}Pu$.

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Table 10. Integral dose of $^{239,240}Pu$ by the inhalation pathway, rem.

	Lung				Liver				Bone			
Island	10 yr	30 yr	50 yr	70 yr	10 yr	30 yr	50 yr	70 yr	10 yr	30 yr	50 yr	70 yr
Bikini	4.6(-2)[a]	0.16	0.28	0.39	3.1(-3)	3.9(-2)	0.11	0.20	3.9(-3)	5.3(-2)	0.16	0.31
Eneu	6.8(-3)	2.4(-2)	4.1(-2)	5.8(-2)	4.5(-4)	5.8(-3)	1.6(-2)	3.0(-2)	5.7(-4)	7.8(-3)	2.3(-2)	4.6(-2)

[a]Numbers in parentheses indicate powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

The concentrations (pCi/g) of ^{241}Am in the soil at Bikini and Eneu are approximately one-half of the ^{239,240}Pu concentrations. However, more ^{241}Am will result from the decay of ^{241}Pu. The parent-daughter relationship for ^{241}Pu/^{241}Am is shown in Fig. 4. The maximum ^{241}Am activity that will result from an initial ^{241}Pu activity is 2.6% of the initial ^{241}Pu activity. Because the present ^{241}Pu activity in the soil is 10 times that of ^{239,240}Pu, the final ^{241}Am soil activity resulting from the decay of ^{241}Pu will be 0.26 that of ^{239,240}Pu. The currently observed ^{241}Am soil concentrations are 0.55 that of ^{239,240}Pu. Thus, the final total soil concentration of ^{241}Am resulting from ^{241}Am now present and that which will result from ^{241}Pu decay will be 0.81 (0.55 + 0.26) that of the existing ^{239,240}Pu soil concentrations. For estimates of dose via inhalation, the eventual ^{241}Am soil concentrations can be considered equal to the ^{239,240}Pu concentrations. As a result, the doses shown in Table 6 for ^{239,240}Pu can be doubled to account for the ^{241}Am.

DRINKING WATER PATHWAY

The analysis of cistern and ground water were published in a separate report.[4] Both radiological and chemical analyses were performed. A summary of the radiological quality of the water is presented here. For more

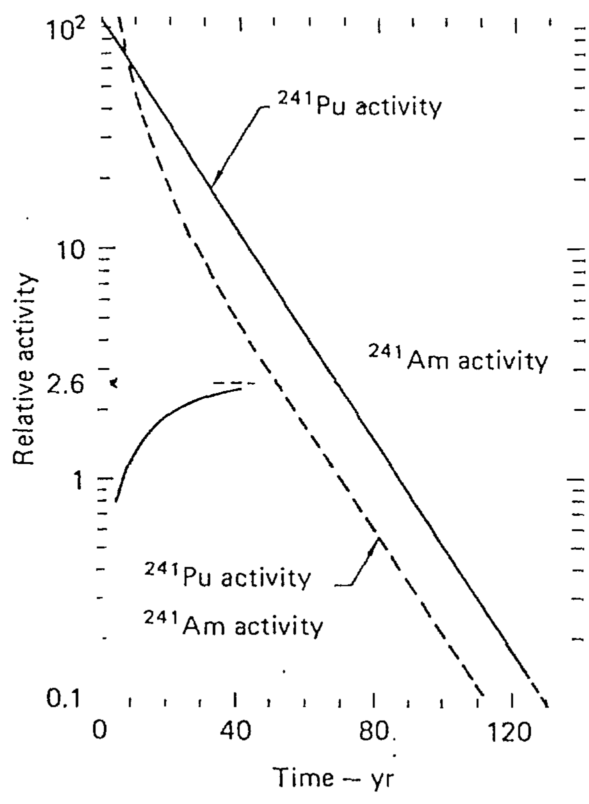

Fig. 4. Relationship between parent ^{241}Pu activity and daughter ^{241}Am activity.

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detail and for data on the chemical quality, the original report should be consulted.

The data from the cistern water in Bikini Island are given in Table 11. Ground water data from Bikini and Eneu are listed in Table 12. It is assumed in the alternate living patterns that only the cistern water will be used for consumption. Therefore, the dose assessment via this pathway was based upon the average values listed in Table 11. The ground water data are presented for comparison in the event ground water were used as potable water.

The 10-, 30-, 50-, and 70-yr integral doses resulting from the consumption of Bikini cistern water are listed in Table 13 and are of the order of a few millirem for whole body and bone marrow. These are the doses used in the subsequent dose summary tables. The whole body and liver dose is contributed almost entirely by ^{137}Cs. Strontium-90 and cesium-137 are approximately two orders of magnitude higher than ^{239,240}Pu in contributing to bone marrow dose. Tables 14 and 15 compare the doses based upon the consumptions of Bikini and Eneu ground water. The 30-, 50-, and 70-yr doses resulting from consumption of Bikini ground water range from 1 to 2 rem for bone marrow and 0.4 to 0.7 rem for whole body. This is a very significant increase over the estimates resulting from consumption of cistern water. The estimates based upon consumption of Eneu ground water (Table 15) also exceed those based upon consumption of cistern water; the 30-, 50-, and 70-yr integral doses range from 0.2 to 0.4 rem for bone marrow and 0.03 to 0.05 rem for whole body. All doses were based upon an intake of water of 2 l/da.

Table 11. Analysis of cistern water sampled on 21 June 1975 on Bikini Island (Bikini Atoll).

Bldg.	Radionuclides (pCi/l)[a] ^{137}Cs	^{90}Sr	^{239,240}Pu
5	2.5(1)	1.1(11)	7.9×10^{-3}(5)
24	1.8(2)	1.9(2)	13.7×10^{-3}(4)
School	1.7(2)	1.42(7)	29.0×10^{-3}(2)
Mean	2.0	1.47	1.69×10^{-2}

[a]The values in parentheses are the 1-σ counting errors expressed as percentage of the listed values.

MARINE FOOD CHAIN

No marine samples were collected during the June 1975 survey. This was the result of both limited manpower and time and the fact that the marine pathway contributed much less to the gamma radiation dose than the terrestrial and external gamma pathways at Enewetak.[29] From this relative point of view, we expected both atolls to be very similar.

Table 12. Radionuclide concentration in the groundwater of Bikini and Eneu Islands.

Bikini

		Concentration[a]						
		^{137}Cs (pCi/l)		^{90}Sr (pCi/l)		$^{239,240}Pu$ (fCi/l)		Ratio $^{238/239,240}Pu$
Well	Time sampled	Sol	Part	Sol	Part	Sol	Part	Sol
HFH 1	(0840)	480	9.9	87(1)	1.31	40.0	3.3(13)	0.026(9)
	(1145)	629	10.9	46(1)	0.57	5.9	1.3(32)	<0.004
	(1545)	695	15.6	38(1)	0.48	4.7	1.9(21)	<0.004
HFH 2		294	12.0	77	1.37	7.5	71.3(4)	0.04 (35)
HFH 3		335	8.3	227		38.2	8.4(10)	<0.008
HFH 4		226	6.5	260		89	33.2	<0.001
HFH 5		530	8.5	180		25.6	13.4(12)	0.004(60)
HFH 7		250	5.8	1.0		0.8	2.0(22)	0.022(30)

Eneu

		Concentration[a]					
		^{137}Cs (pCi/l)		^{90}Sr (pCi/l)		^{239}Pu (fCi/l)	
Well	Time sampled	Sol	Part	Sol	Part	Sol	Part
FWR 1	0835	35.3(1)	1.17(2)	71 (1)	0.81	3.5(6)	9.5 (10)
	1250	30 (1)	0.73(3)	45.6(1)	0.56	3.3(8)	1.6 (22)
FWR 2		69.1(1)	0.95(3)	66 (2)		23.5(4)	8.4 (17)
FWR 3S[b]		32 (2)	0.59(2)	1.3(13)	0.03	0.72(22)	1.42(16)
3B[b]		20 (3)	0.49(5)	1.0(9)		0.32(30)	1.1 (15)
FWR 4		1.1(5)	0.57(2)	3.4(5)	0.11	0.85(18)	0.67(27)

[a]Sol = soluble fraction, Part = particulate fraction. The values in parentheses are the 1-σ counting errors expressed as percentages of the listed values.

[b]S = surface, B = bottom.

The data used, therefore, to evaluate the potential dose via the marine food chain was obtained from published data[8,30] and from unpublished data supplied through the courtesy of Dr. Vic Nelson of the Laboratory of Radiation Ecology, University of Washington. Table 16 lists the fish data used in the dose assessment. Table 17 lists the data on clams. The average concentration of the radionuclides were determined from the data

Table 13. Bikini cistern water — integral dose, rem.

	10 yr			30 yr			50 yr			70 yr		
Radio-nuclide	WB[a]	Bone morrow	Liver	WB[a]	Bone marrow	Liver	WB[a]	Bone marrow	Liver	WB[a]	Bone marrow	Liver
^{137}Cs	7.5(-4)[b]	7.5(-4)	7.5(-4)	1.9(-3)	1.9(-3)	1.9(-3)	2.6(-3)	2.6(-3)	2.6(-3)	3.0(-3)	3.0(-3)	3.0(-3)
^{90}Sr	—	3.1(-3)	—	—	9.1(-3)	—	—	1.3(-2)	—	—	1.5(-2)	—
$^{239,240}Pu$	—	6.9(-6)	5.4(-6)	—	5.9(-5)	4.4(-5)	—	1.6(-4)	1.1(-4)	—	3.0(-4)	1.9(-4)
Total	7.5(-4)	3.8(-3)	7.5(-4)	1.9(-3)	1.1(-2)	1.9(-3)	2.6(-3)	1.6(-2)	2.7(-3)	3.0(-3)	1.9(-2)	3.2(-3)

[a]WB = whole body.

[b]Numbers in parentheses indicate powers of 10, i.e., (-4) indicates × 10^{-4}.

Table 14. Bikini ground water — integral dose, rem.

	10 yr			30 yr			50 yr			70 yr		
Radio-nuclide	WB[a]	Bone marrow	Liver	WB[a]	Bone marrow	Liver	WB[a]	Bone marrow	Liver	WB[a]	Bone marrow	Liver
^{137}Cs	0.16	0.16	0.16	0.41	0.41	0.14	0.56	0.56	0.56	0.66	0.66	0.66
^{90}Sr	—	0.24	—	—	0.73	—	—	1.0	—	—	1.2	—
$^{239,240}Pu$	—	1.1(-5)[b]	8.8(-6)	—	9.7(-5)	7.1(-5)	—	2.6(-4)	1.8(-4)	—	4.8(-4)	3.2(-4)
Total	0.16	0.41	0.16	0.41	1.1	0.41	0.56	1.6	0.56	0.66	1.9	0.66

[a]WB = whole body.

[b]Numbers in parentheses indicate powers of 10, i.e., (-5) indicates × 10^{-5}.

Table 15. Eneu ground water — integral dose, rem.

Radio nuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	1.2(-2)[b]	1.17(-2)	1.2(-2)	2.9(-2)	2.9(-2)	2.9(-2)	4.0(-2)	4.0(-2)	40.0(-2)	4.7(-2)	4.7(-2)	4.7(-2)
^{90}Sr	—	6.6(-2)	—	—	0.20	—	—	0.28	—	—	0.33	—
$^{239,240}Pu$	—	2.2(-6)	1.7(-6)	—	1.9(-5)	1.4(-5)	—	5.0(-5)	3.5(-5)	—	9.4(-5)	6.2(-5)
Total	1.2(-2)	7.7(-2)	1.2(-2)	2.9(-2)	0.22	2.9(-2)	4.0(-2)	0.32	4.0(-2)	4.7(-2)	0.37	4.7(-2)

[a]WB = whole body.

[b]Numbers in parentheses indicates powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

Table 16. Radionuclide concentration in fish at Bikini Atoll.

Date collected	Island	Species	Tissue	No. in sample	Concentration, pCi/g dry weight ^{60}Co	^{137}Cs	^{90}Sr	$^{239,240}Pu$	Source
Apr 1975	Eneu	Goatfish	EW[a]	5	1.6	0.18	0.23	0.003	Vic Nelson,
"	"	"	EW	8	1.0	0.18	<0.07	0.003	unpublished
"	"	Convict surgeon	EW	6	0.27	0.25	0.07	—	"
"	"	"	EW	6	0.19	0.18	<0.07	0.005	"
"	"	Grouper	Muscle	1	0.16	0.43	<0.03	—	"
"	"	Parrot fish	Muscle	1	—	0.43	<0.03	—	"
Dec 1974	Namu	Convict surgeon	EW	10	1.7	4.5	<0.26	—	"
"	Enidrik	"	EW	12	0.68	0.48	0.17	0.020	"
Dec 1974	Namu	Mullet	EW	9	2.0	0.32	0.12	<0.01	"
"	Enidrik	"	EW	4	0.82	0.14	0.05	<0.002	"
"	"	"	EW	2	1.4	0.32	<0.06	0.008	"
Apr 1974	Bikini	Goatfish	Entire	1	—	—	0.06	0.004	"
"	"	Mullet	EW	3	3.50	0.12	0.24	0.020	"
"	"	"	EW	3	1.90	0.72	0.18	0.045	"
May 1972	Namu	Mullet	EW	14	4.3	0.25	—	—	Lynch *et al.*[8]
"	"	"	EW	12	4.1	0.59	0.16	—	"
"	"	"	EW	2	18	1.2	—	—	"
"	Bikini	Convict surgeon	EW	10	1.0	0.7	—	—	"
"	"	"	EW	14	0.9	0.51	0.15	—	"
"	Eneman	"	EW	16	1.0	0.20	0.07	—	"
"	"	Goatfish	EW	1	0.67	0.08	<0.03	—	"
"	Nam	"	EW	12	26	0.51	1.0	—	"
"	"	Snapper	Muscle	6	3.2	0.99	—	—	"

Table 16. (Cont)

Date collected	Island	Species	Tissue	No. in sample	Concentration, pCi/g dry weight ^{60}Co	^{137}Cs	^{90}Sr	$^{239,240}Pu$	Source
Oct 1972	Bikini	Surgeon fish	Muscle	3	—	—	—	0.0016	Nevissi &
"	Bokbata	"	EW	1	—	—	—	0.028	Schell[26]
"	Several	Convict surgeon	Muscle	39	—	—	—	<0.0016	"
"	Bokbata	"	EW	4	—	—	—	0.044	"
"	Nam	"	EW	1	—	—	—	0.016	"
"	"	"	EW	4	—	—	—	0.027	"

[a]EW = eviscerated whole fish.

Table 17. Radionuclide concentrations in clams at Bikini Atoll.

Date Collected	Species	Tissue	Concentration, pCi/g dry weight ^{60}Co	^{137}Cs	^{90}Sr	$^{239,240}Pu$	Source
Nov 1972	*Tridacna gigas*	Muscle	0.2	<0.05	—	—	Bill Schell, unpublished
"	*Tridacna crocea*	Muscle + mantle	5.5	<0.05	—	—	"
"	*Hippopus sp.*	" "	4.9	<0.05	—	—	"
"	*Tridacna crocea*	" "	32	<0.05	—	—	"
Apr 1975	*Tridacna gigas*	Mantle	9.5	<0.05	<0.03	0.04	Vic Nelson, unpublished
"	" "	Muscle	4.9	0.17	<0.03	0.012	"

in Tables 16 and 17 by weighting by sample size and by assuming that detection limit values ("less than" numbers) were actual concentration values. Table 18 lists the final radionuclide concentrations that were used along with the estimate of fish ingested per day (600 g/da) to calculate the radionuclide intake via the marine food chain (pCi/da). The table also includes the concentration of some radionuclides in fish used in the 1973 Enewetak assessment.

The species of birds that are readily caught and included in the diet are marine feeders, mostly species of terns. Therefore, the radionuclide concentrations in their muscle tissue are similar to that in the marine diet. For this reason, birds and bird eggs are considered part of the marine diet for the purposes of dose calculation. No birds or bird eggs were collected in June 1975, so the data used to evaluate this part of the marine food chain come from previously published reports[8,31,32] and are summarized in Table 19. The final concentration data used for dose assessment listed in Table 20 were derived assuming that six times more bird muscle is consumed than liver and that the wet-to-dry ratio is 0.33 for muscle and liver and 0.25 for eggs. Because of the absence of Pu concentration data on birds and bird eggs on Bikini and the similarity of Bikini and Enewetak data on bird muscle and liver, we are listing in Table 20 the Pu concentrations from the Enewetak Radiological Survey.[33]

The 10-, 30-, 50-, and 70-yr integral doses resulting from ingestion of marine foods are given in Table 21. Strontium-90 contributes the largest fraction of the bone marrow dose (70 to 80%), ^{137}Cs contributes approximately 20%, while ^{60}Co and ^{239,240}Pu contribute about 6% of the total. The whole body dose from the marine pathway is 50 mrem for the integrated 30-yr dose and 66 mrem for the 50-yr integrated dose. The bone marrow doses are 200 mrem and 290 mrem for the 30-yr and 50-yr integral doses, respectively. These integral doses are small relative to those from other pathways. Although the marine pathway contributes a relatively significant fraction of the total ^{239,240}Pu intake,

Table 18. Average weighted[a] radionuclide concentrations in fish and clams at Bikini Atoll.

Species	Concentration, pCi/g Wet Weight			
	^{60}Co	^{137}Cs	^{90}Sr	^{239,240}Pu
Fish	1.51	0.14	0.076	0.0028
Clams	2.06	0.011	0.0060	0.0072
Enewetak Atoll 1972 Dose Assessment				
Fish	2.0	0.39	0.075	—

[a]Weighted by number of fish or clams in the sample.

Table 19. Radionuclide concentrations in birds and bird eggs at Bikini Atoll.

Source	Island	Species	Sample	Tissue	Concentration, pCi/g wet weight ^{60}Co	^{137}Cs	^{90}Sr	$^{239,240}Pu$
Lynch *et al*[8]	Oroken	Fairy tern	1	Muscle	0.26	0.079	—	—
Held[28]	"	Noddy tern	5	Muscle	1.3	0.15	—	—
"	"	" "	5	Liver	2.7	<0.4	—	—
"	"	Fairy tern	5	Muscle	0.29	<0.4	—	—
"	"	" "	5	Liver	0.42	<0.4	—	—
Vic Nelson,[27] unpublished	Nam	Sooty and noody tern	4	Muscle	0.30	<0.017	0.013	—
"	"	Bird eggs	—	Shelled egg	0.06	0.13	0.07	—

the resulting dose compared to ^{90}Sr and ^{137}Cs is very small.

TERRESTRIAL FOOD CHAIN

The availability of locally grown terrestrial food products was still minimal in June 1975. Thousands of coconut trees were planted in the latter half of 1969 on Bikini and Eneu, but only a few were bearing fruit in 1975. Pandanus fruit and breadfruit were planted during the same time period on Bikini Island, and the first few fruits from these trees appeared over the past year and a half. The number of these trees is, however, not great and their distribution is limited. No breadfruit or Pandanus fruit were planted on Eneu. Banana and papaya trees were also planted at two locations on Bikini Island and produced fruit during the past two years.

Table 20. Average radionuclide concentrations in birds and bird eggs at Bikini Atoll.

	Concentration, pCi/g wet weight ^{60}Co	^{137}Cs	^{90}Sr	$^{239,240}Pu$
Birds	0.76	0.22	0.04	0.022
Bird eggs	0.015	0.033	0.018	0.0059

As a result of the sparsity of available food crops, our goals in the limited survey were to sample the vegetation of all species of food crops available as well as indicator plants such as *Scaevola* and *Messerschmidia*, to sample edible fruit where available, and to take soil profile

Table 21. Marine food chain — integral dose, rem.

Radio-nuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	1.7(-2)[b]	1.7(-2)	1.7(-2)	4.2(-2)	4.2(-2)	4.2(-2)	5.8(-2)	5.8(-2)	5.8(-2)	6.8(-2)	6.8(-2)	6.8(-2)
^{60}Co	6.1(-3)	6.1(-3)	6.1(-3)	8.1(-3)	8.1(-3)	8.3(-3)	8.3(-3)	8.3(-3)	8.3(-3)	8.3(-3)	8.3(-3)	8.3(-3)
^{90}Sr	—	5.0(-2)	—	—	1.5(-1)	—	—	2.1(-1)	—	—	2.5(-1)	—
$^{239,240}Pu$	—	4.9(-4)	3.8(-4)	—	4.2(-3)	3.1(-3)	—	1.1(-2)	7.8(-3)	—	2.1(-2)	1.4(-2)
Total	2.3(-2)	7.4(-2)	2.3(-2)	5.0(-2)	2.0(-1)	5.3(-2)	6.6(-2)	2.9(-1)	7.4(-2)	7.6(-2)	3.5(-1)	9.0(-2)

[a]WB = whole body.

[b]Numbers in parentheses indicate powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

samples through the root zones of the sampled trees. From these data, we developed concentration factors (CF) relating concentration in food products to soil concentration, as well as concentration ratios that relate the concentration in the vegetation (leaf) to the concentration in the edible fruit, or the concentration in indicator species (*Scaevola* and *Messerschmidia*) to concentrations in food crops.[5]

A separate report[5] discusses in detail the results of the sampling program and the calculation of CF and concentation ratio. In brief, the distribution of radionuclides in both the Bikini and Enewetak environment was nonhomogenous. Radionuclide concentrations in soil varied greatly over distances of only a few feet. The results of our work during this survey verified our thesis that because of the wide variability in soil concentration with location, useful concentration factors can only be calculated from vegetation and soil data sampled from the exact site. Concentration factors derived from soil sampled from the root zone of the vegetation under investigation showed a greatly reduced range of values compared with values developed earlier from vegetation and soil samples from different sites but in the same area[34,35] (see also Table 22, this report).

The concentration factors determined from this survey are more precise and provide a better basis for estimating the average radionuclide concentration that would be expected from crops planted in certain regions within an island or on different islands.

Despite the greater precision of concentration factors calculated from associated vegetation and soil data; these values still show some variability. This remaining variability can be accounted for by several factors acting either alone or in concert. These factors include differences in:

- Soil type, organic content, and chemical characteristics;
- Physiochemical properties of the radionuclides;
- Soil management practices;
- Irrigation practices; and
- Physiology, age, and prior history of the sampled plants.

One would, in fact, expect to see some variation in sampling conducted from a specific tree merely resulting from normal biological variability.

In addition to the calculation of CF, the data from the large surface-soil sampling program[5] were used to determine average soil concentrations in four regions on Bikini Island and in the whole of Eneu Island. These average soil concentrations were then used along with the concentration factors to predict the radionuclide

Table 22. Soil-mature leaf concentration factors calculated from associated[a] and nonassociated[b] data.

	Concentration factor, (pCi/g dry plant) (pCi/g dry soil)							
	Associated				Nonassociated			
Nuclide species	No. of samples	Min	Max	Median	No. of samples	Min	Max	Median
^{90}Sr, *Scaevola*	2	0.24	0.41	0.33	4	0.048	4.3	1.8
^{90}Sr, coconut	7	0.099	0.38	0.16	15	0.041	0.74	0.29
^{137}Cs, *Scaevola*	2	1.3	14	7.5	4	0.073	39	7.7
^{137}Cs, coconut	8	1.1	16	3.0	15	0.53	18	2.6
^{239}Pu, coconut	4	0.011	0.022	0.015	12	0.0036	0.14	0.016
^{240}Pu, coconut	4	0.011	0.021	0.015	12	0.0021	0.15	0.016

[a]Plant and soil data sampled from the same site.

[b]Plant and soil data sampled from different sites in the same general area.

concentrations expected in the terrestrial food products. The results are listed in Table 23.

During the June survey, a fully grown pig and two chickens that were born in and raised on Bikini Island were obtained for analysis. The pig and chickens roamed freely around the island, so the radionuclide concentrations in these animals reflect their integrated diet. Ingestion via the meat pathway can be estimated by the analysis of these samples. The estimates of the radionuclide concentration expected in meat on Eneu were determined by multiplying the concentrations in the meat samples from Bikini Island by the ratio of the average Eneu-Bikini soil concentrations. Since most of the animal diet consists of vegetation and a certain amount of soil, this ratioing procedure should predict reasonable concentrations for domestic animals raised on Eneu.

Although coconut crabs were not collected during the June 1975 survey, they were collected during previous visits to the islands. The values listed for coconut crab in Table 23 were determined from data from collections in 1969, 1972, and 1974.[8,31,32]

Concentrations in food products after June 1975 are calculated assuming that the only loss of radionuclides from the environment is the result of the physical decay of each radionuclide.

Table 23. Measured and estimated radionuclide concentrations in food products on Bikini and Eneu Islands at Bikini Atoll.

Food product	Concentration, pCi/g wet weight 1 January 1975 ^{90}Sr	^{137}Cs	^{60}Co	$^{239,240}Pu$
	Bikini terrestrial foods			
Pandanus fruit	7.60	46.7	<1.30(-2)[a]	<4.81(-3)
Breadfruit	17.3	90.5	<3.59(-2)	<6.12(-3)
Coconut meat (dry wt)	1.82	108	<0.111	<1.06(-2)
Coconut milk	0.851	50.6	<0.103	<9.01(-3)
Domestic meat	0.201	22.2	<1.05(-2)	<1.42(-2)
Coconut crabs	220	47.6	1.09	6.8(-3)
Garden vegetables	12.9	56.7	7.40(-3)	<5.56(-4)
	Eneu terrestrial foods			
Pandanus fruit	0.407	3.09	<1.02(-3)[a]	<3.96(-4)
Breadfruit	0.924	5.99	<2.82(-3)	<5.03(-4)
Coconut meat (dry wt)	9.76(-2)	7.16	<8.74(-3)	<1.86(-2)
Coconut milk	4.56(-2)	3.35	<8.07(-3)	<7.41(-3)
Domestic meat	<1.08(-2)	1.47	<8.24(-4)	<1.17(-3)
Coconut crabs	220	47.6	1.09	6.8(-3)
Garden vegetables	0.689	3.75	5.82(-4)	<4.57(-5)

[a]Numbers in parentheses indicates powers of 10, i.e., (-2) indicates $\times 10^{-2}$.

This conservative approach was adopted because we lack any definitive information that would indicate that environmental processes might result in more rapid, effective removal of radionuclides from the environment. Any environmental process that might cause the removal of radionuclides from the environment more rapidly than the physical decay of the radionuclides would, of course, reduce the predicted concentrations in the food products and, as a result, would reduce the predicted doses via the terrestrial pathway.

The dietary intake values in Table 3 and the concentrations in Table 23 were used to generate the pCi/da intake of each of the radionuclides. The results in Table 24 are for a diet entirely from Eneu Island, while those in Table 25 are for a diet solely from

Table 24. Total diet from Eneu.

Nuclide	Intake, pCi/da 1975[a]	1980
^{60}Co	29.1	35
^{137}Cs	2575	4243
^{90}Sr	270	412
$^{239,240}Pu$	0.438	0.740

[a]Minus Pandanus fruit and breadfruit.

Bikini Island. Table 26 lists the pCi/da intake for a diet originating from Bikini Island, excluding Pandanus fruit and breadfruit. The diet for 1980 includes the contribution from Pandanus fruit and breadfruit from Eneu Island. Table 27 lists the pCi/da intake for a diet that only allows the use of coconut from Bikini Island. In other words, the rest of the diet is from Eneu. The data are used with the various living patterns as follows:

Living Pattern	Intake Data
1	Table 24
2	Table 27
3	Table 26
4	Table 27
5	Table 26
6	Table 25

The data for Bikini Island were broken down by the areas shown in Fig. 2. However, because subsistence agriculture could come from any of the four areas and because the results do not differ greatly by area, the average value of the four areas on Bikini were used for the dose assessment. Because of the relatively uniform concentration of radionuclides observed on Eneu, only one set of intake values was calculated based upon the island's average soil concentration.

The integral 10-, 30-, 50-, and 70-yr doses to the whole body, bone

Table 25. Total diet from Bikini Island.

	Intake, pCi/da									
	Area 1		Area 2		Area 3		Area 4		Mean of areas 1,2,3 and 4	
Nuclide	1975	1980	1975	1980	1975	1980	1975	1980	1975	1980
^{60}Co	45	33	46	44	55	43	54	42	52.5	40.5
^{137}Cs	23,577	39,427	28,893	48,986	31,498	53,685	31,997	54,595	28,991	49,173
^{90}Sr	1415	2726	3810	7841	2186	3882	2163	3836	2394	4571
$^{239,240}Pu$	3.44	5.89	5.15	9.86	3.27	5.48	4.0	7.18	3.97	7.10

Table 26. Bikini diet minus Pandanus and breadfruit.

Intake, pCi/da

	Area 1		Area 2		Area 3		Area 4		Mean of areas 1,2,3 and 4	
Nuclide	1975	1980	1975	1980	1975	1980	1975	1980	1975	1980
^{60}Co	43.3	32.4	53.2	42.6	52.3	41.8	51.4	40.9	50.1	39.4
^{137}Cs	18,175	24,668	22,060	29,994	23,965	32,612	24,330	33,119	22,133	30,098
^{90}Sr	737	931	1750	1997	1064	784	1054	779	1151	1123
$^{239,240}Pu$	3.02	4.58	4.34	7.19	2.88	4.30	3.45	5.42	3.42	5.37

Table 27. Eneu diet with coconut from Bikini.

Intake, pCi/da

	Area 1		Area 2		Area 3		Area 4		Mean of areas 1,2,3 and 4	
Nuclide	1975	1980	1975	1980	1975	1980	1975	1980	1975	1980
^{60}Co	41.8	33	51.4	42.8	50.5	41.9	49.9	41.3	48.4	39.8
^{137}Cs	14,049	20,991	17,347	25,794	18,963	28,155	19,272	28,612	17,408	25,888
^{90}Sr	401	604	698	1035	497	743	494	738	523	780
$^{239,240}Pu$	1.74	3.25	3.04	5.85	1.60	2.41	2.16	4.10	2.14	3.90

marrow, and liver of each radionuclide via the terrestrial food chain are listed in Table 28 for Eneu Island and Table 29 for Bikini Island. The altered diets are listed in Table 30 and 31. Table 30 represents the Bikini diet minus the Pandanus fruit and breadfruit, and Table 31 reflects the doses for the case in which the diet is from Eneu with the exception of coconut from Bikini. The Bikini data represent the average of areas 1, 2, 3, and 4 as previously described.

Focusing on the 30-yr integral dose for the total diets from each island (Tables 28 and 29), it is clear that ^{137}Cs accounts for nearly all of the whole body exposure. Cesuim-137 accounts for approximately 60% of the bone marrow dose, while ^{90}Sr accounts for the remaining 40%. Contributions of ^{60}Co and $^{239,240}Pu$ via the terrestrial food chain are relatively insignificant. Integral doses from ^{241}Am would be similar to the predicted doses from $^{239,240}Pu$. The 30-yr integral

Table 28. Terrestrial food chain on Eneu Island — integral dose, rem.

Radionuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	6.7(-1)[b]	6.7(-1)	6.7(-1)	2.0	2.0	2.0	2.8	2.8	2.8	3.3	3.3	3.3
^{90}Sr	—	3.6(-1)	—	—	1.3	—	—	1.9	—	—	2.3	—
^{60}Co	3.3(-4)	3.3(-4)	3.3(-4)	5.4(-4)	5.4(-4)	5.4(-4)	5.6(-4)	5.6(-4)	5.6(-4)	5.6(-4)	5.6(-4)	5.6(-4)
$^{239,240}Pu$	—	1.0(-4)	8.05(-5)	—	1.1(-3)	8.3(-4)	—	3.2(-3)	2.21(-3)	—	6.1(-3)	4.0(-3)
Total	0.67	1.03	.67	2.0	3.3	2.0	2.8	4.7	2.8	3.3	6.6	3.3

[a]WB = whole body.

[b]Numbers in parentheses indicate powers of 10, i.e., (-1) indicates $\times 10^{-1}$.

Table 29. Terrestrial food chain on Bikini Island — integral dose, rem. Bikini average of Areas 1, 2, 3, and 4.

Radionuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	7.6 [1.1][b]	7.6 [1.1]	7.6 [1.1]	23 [3.2]	23 [3.2]	23 [3.2]	33 [4.5]	33 [4.5]	33 [4.5]	39 [5.4]	39 [5.4]	39 [5.4]
^{90}Sr	—	3.6 [1.7]	—	—	14 [6.7]	—	—	21 [10]	—	—	25 [12]	—
^{60}Co	5.0(-4)[c] [4.8(-5)]	5.0(-4) [4.8(-5)]	5.0(-4) [4.8(-5)]	7.8(-4) [8.1(-5)]	7.8(-4) [8.1(-5)]	7.8(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]	8.0(-4) [8.1(-5)]
$^{239,240}Pu$	—	9.0(-4) [2.0(-4)]	7.1(-4) [1.5(-4)]	—	1.1(-2) [2.7(-3)]	7.7(-3) [2.0(-3)]	—	3.0(-2) [8.0(-3)]	2.1(-2) [5.5(-3)]	—	5.8(-2) [1.6(-2)]	3.8(-2) [1.0(-2)]
Total	7.6	11	7.6	23	37	23	33	53	33	39	63	39

[a]WB = whole body.

[b][σ in brackets]

[c]Numbers in parentheses indicate powers of 10, i.e., (-4) indicates 10^{-4}.

Table 30. Terrestrial food chain on Bikini Island, minus Pandanus and breadfruit — integral dose, rem. Bikini average of Areas 1,2,3, and 4 minus Pandanus and breadfruit.

Radio-nuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	5.1 [0.66][b]	5.1 [0.66]	5.1 [0.66]	14 [1.9]	14 [1.9]	14 [1.9]	20 [2.6]	20 [2.6]	20 [2.6]	24 [3.1]	24 [3.1]	24 [3.1]
^{90}Sr	—	1.3 [0.53]	—	—	3.9 [1.9]	—	—	5.5 [2.7]	—	—	6.5 [3.2]	—
^{60}Co	4.8(-4)[c] [4.7(-5)]	4.8(-4) [4.7(-5)]	4.8(-4) [4.7(-5)]	7.4(-4) [8.0(-5)]	7.4(-4) [8.0(-5)]	7.4(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]	7.6(-4) [8.0(-5)]
$^{239,240}Pu$	—	7.6(-4) [1.5(-4)]	5.9(-4) [1.2(-4)]	—	8.2(-3) [1.9(-3)]	6.0(-3) [1.4(-3)]	—	2.3(-2) [5.3(-3)]	1.6(-2) [3.7(-3)]	—	4.5(-2) [1.0(-2)]	2.9(-2) [6.9(-3)]
Total	5.1	6.4	5.1	14	18	14	20	26	20	24	31	24

[a]WB = whole body.

[b][σ in brackets].

[c]Numbers in parentheses indicate powers of 10, i.e., (-4) indicates $\times 10^{-4}$.

Table 31. Terrestrial food chain on Bikini Island with Eneu diet plus coconut from Bikini — integral dose, rem. Bikini average of Areas 1,2,3, and 4 with Eneu diet plus only coconut from Bikini Island.

Radio-nuclide	10 yr WB[a]	10 yr Bone marrow	10 yr Liver	30 yr WB[a]	30 yr Bone marrow	30 yr Liver	50 yr WB[a]	50 yr Bone marrow	50 yr Liver	70 yr WB[a]	70 yr Bone marrow	70 yr Liver
^{137}Cs	4.2 [0.58][b]	4.2 [0.58]	4.2 [0.58]	12 [1.6]	12 [1.6]	12 [1.6]	17 [2.3]	17 [2.3]	17 [2.3]	21 [2.8]	21 [2.8]	21 [2.8]
^{90}Sr	—	0.69 [0.16]	—	—	2.5 [0.58]	—	—	3.6 [0.84]	—	—	4.3 [1.0]	—
^{60}Co	4.7(-4)[c] [3.9(-5)]	4.7(-4) [3.9(-5)]	4.7(-4) [3.9(-5)]	7.3(-4) [6.7(-5)]	7.3(-4) [6.7(-5)]	7.3(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]	7.5(-4) [6.7(-5)]
$^{239,240}Pu$	—	5.1(-4) [1.6(-4)]	4.0(-4) [1.2(-4)]	—	5.8(-3) [2.1(-3)]	4.3(-3) [1.5(-3)]	—	1.7(-2) [6.0(-3)]	1.2(-2) [4.2(-3)]	—	—	—
Total	4.2	4.9	4.2	12	15	12	17	21	17	21	25	21

[a]WB = whole body.

[b][σ in brackets].

[c]Numbers in parentheses indicate powers of 10, i.e., (-4) indicates $\times 10^{-4}$.

dose via the terrestrial foodchain on Bikini Island is 23 rem for whole body and 37 rem for bone marrow compared to Eneu Island where the respective doses are 2.0 rem and 3.3 rem. The 50-yr integral doses, of course, show a similar difference. It is clear that the living pattern on Eneu Island is much preferred to that on Bikini Island for reducing potential dose to returning populations.

The impact of removing Pandanus fruit and breadfruit grown on Bikini Island from the diet can be seen in Table 31. The bone marrow doses are reduced by nearly one-half (a 30-yr dose of 18 rem and a 50-yr dose of 20 rem), while whole body doses are reduced by approximately 40% (a 30-yr dose of 14 rem and a 50-yr dose of 20 rem). Removing all other items from Bikini Island from the diet with the exception of coconut, i.e., Eneu diet plus Bikini Island coconut, gives a further reduction in bone marrow and whole body dose of approximately 20% over removing Pandanus fruit and breadfruit only (see Table 31). However, comparing the Eneu only diet in Table 28 and the Eneu diet plus coconut from Bikini Island in Table 31, it is clear that inclusion of coconut from Bikini Island increases significantly the bone marrow and whole body doses relative to a diet totally derived from Eneu Island. For comparison, the 50-yr bone marrow dose from a diet derived totally from Eneu is 4.7 rem, while the Eneu diet plus coconut from Bikini leads to a dose of 21 rem. The 50-yr whole body doses from the two diets are 2.8 rem and 17 rem, respectively.

Dose Summary and Discussion

Tables 6 through 9 list the 10-, 30-, 50- and 70-yr integral doses for each exposure pathway, plus the sum of all exposure pathway for each of the six living patterns. As an example, the 30-yr integral dose in Table 7 will be examined.

For Pattern 1 (living on Eneu Island and diet from Eneu Island), the terrestrial diet contributes 57% of the bone marrow dose and 48% of the whole body dose. The external gamma dose contributes nearly 36% of the bone marrow dose and 50% of the whole body dose. The marine and drinking water pathways, assuming that the drinking water on Eneu is from the ground water system, each contribute about 3% to the bone marrow dose and 1% or less to the whole body. Therefore, in Pattern 1, 93% of the bone marrow dose and 98% of the whole body dose are contributed by two pathways, terrestrial and external. For tern 6, living on Bikini Island and diet from Bikini Island, the terrestrial and external gamma pathways contribute approximately 88% and 12% of the bone marrow dose and approximately 82% and 18% of the whole body dose, respectively. In other words, 99% of the total dose in Pattern 6 results from the terrestrial and external gamma pathways. The integral 30-yr doses for bone marrow range from 5.8 rem in Pattern 1 (Eneu) to 42 rem in Pattern 6 (Bikini). The corresponding whole body doses are 4.2 rem in Pattern 1 to 28 rem in Pattern 6.

As dietary remedial measures are taken on Bikini Island, that is Patterns 2, 3, 4, and 5, which are variations of Pattern 6, the relative contribution of the exposure pathways to total dose changes. However, the pathways that contribute the largest fraction of the total dose continue to be the terrestrial food chain and external gamma pathways. A summary of the percentage contribution of each pathway to total dose in each living pattern is listed in Table 32.

The summation of the 30-yr and 50-yr integral doses for bone marrow and whole body in the six living patterns is listed in Table 33. The Eneu living pattern, Pattern 1, results in the lowest dose. All other living patterns lead to doses at least three times higher, and with the unmodified Bikini living pattern, Pattern 6, the doses are at least six times higher than with the Eneu living Pattern 1. It is clear, therefore, that Eneu Island provides by a significant degree the lowest dose living pattern at Bikini Atoll.

For comparison, the Federal guidelines for whole body and bone marrow dose for a member of the population is 0.5 rem/yr.[23-26] Over a 30-yr period, the guideline for a population is 5 rem. The Eneu living pattern (Pattern 1) leads to predicted 30-yr doses for whole body and bone marrow of 4.2 rem and 5.8 rem, respectively, which are near the Federal guidelines. Pattern 6 (the Bikini Island living pattern) results in predicted 30-yr doses of 28 rem for the whole body and 42 rem for the bone marrow; these doses are approximately 6 to 8 times the Federal guidelines. The other living patterns (Patterns 2 through 5), which include various remedial measures and are variations of the basic Pattern 6 living pattern, lead to predicted whole body doses that range from 16 to 19 rem and bone marrow doses that range from 18 rem to 24 rem. All of these are in excess of the Federal guidelines.

Table 32. Percentage of total 30-yr integral bone marrow dose.

Living pattern	Inhalation	External[a]	Marine	Terrestrial	Water
1	0.13	36	3.4	57	3.8
2	0.29	19	1.1	83	0.06
3	0.24	15	0.91	82	0.05
4	0.28	21	0.1	79	0.06
5	0.22	21	0.83	75	0.05
6	0.13	12	0.48	88	0.03

[a]Natural background subtracted.

Percentage of total 30-yr integral whole body dose.

Living pattern	Inhalation	External[a]	Marine	Terrestrial	Water
1	—	50	1.2	48	0.69
2	—	22	0.31	75	0.01
3	—	18	0.28	78	0.01
4	—	25	0.31	75	0.01
5	—	27	0.26	74	0.01
6	—	18	0.18	82	0.007

[a]Natural background subtracted.

Table 33. Summation of all exposure pathways (natural background subtracted).

Living pattern	Integral 30-yr dose, rem		Integral 50-yr dose, rem	
	Whole body	Bone marrow	Whole body	Bone marrow
1	4.2	5.8	5.8	8.2
2	16	18	22	26
3	18	22	25	31
4	16	19	23	27
5	19	24	28	34
6	28	42	40	61

Comparison with Enewetak Atoll

Both Bikini and Enewetak Atolls were sites for the United States nuclear testing program for 1946 to 1958. Recent requests by both the Bikini and Enewetak people to return to their home atolls have led to detailed radiological surveys to determine the status of the atolls so that the impact, if any, of restrictions placed upon living patterns and life styles as a result of the dose assessment can be estimated. The atolls are located within 180 nautical miles of each other in the northern Marshall Islands. They have essentially the same topography, soil chemistry, rainfall, and biota. In addition to these physical similarities, the distribution of radionuclide contamination in the islands used for residence and the potential impact upon living patterns are somewhat similar.

At Enewetak Atoll the major residence islands of the Enewetak people prior to their relocation in 1947 were Engebi Island in the northern half of the atoll and Enewetak, Medren, and Japtan Islands in the southern half of the atoll (see Fig. 5). The people living on Engebi Island (dri Engebi) had their own chief (Iroj) and owned land rights in the northern islands, and the people living on Enewetak Island (dri Enewetak) also had their own chief and owned land rights in the southern half of the atoll. Many tests were conducted in the northern half of the atoll; and we found that the major residence island, Engebi, was contaminated. The southern half of the atoll, on the other hand, is relatively "clean". The results of the Enewetak assessment indicate that a living pattern involving Engebi Island for both residence and agriculture involves potential doses in excess of regulatory guides, while living patterns in the southern half of the atoll lead to doses similar to those in the United States (1).

The situation of Bikini Atoll is somewhat similar. The two major islands used for residence were Bikini and Eneu (see Fig. 1). The people living on Bikini Island own land rights on that island as do those people living on Eneu. Bikini Island was heavily contaminated as a result of the Bravo event; Eneu was contaminated to a lesser degree, but, as will be seen, is still more contaminated than the southern half of Enewetak Atoll.

The survey of Enewetak Atoll was conducted in 1972-73 and the resulting assessment published in 1973.[36] Additional information on annual doses and impacts of remedial actions were published in the AEC Task Group Report.[37] Recommendations on the use of Enewetak

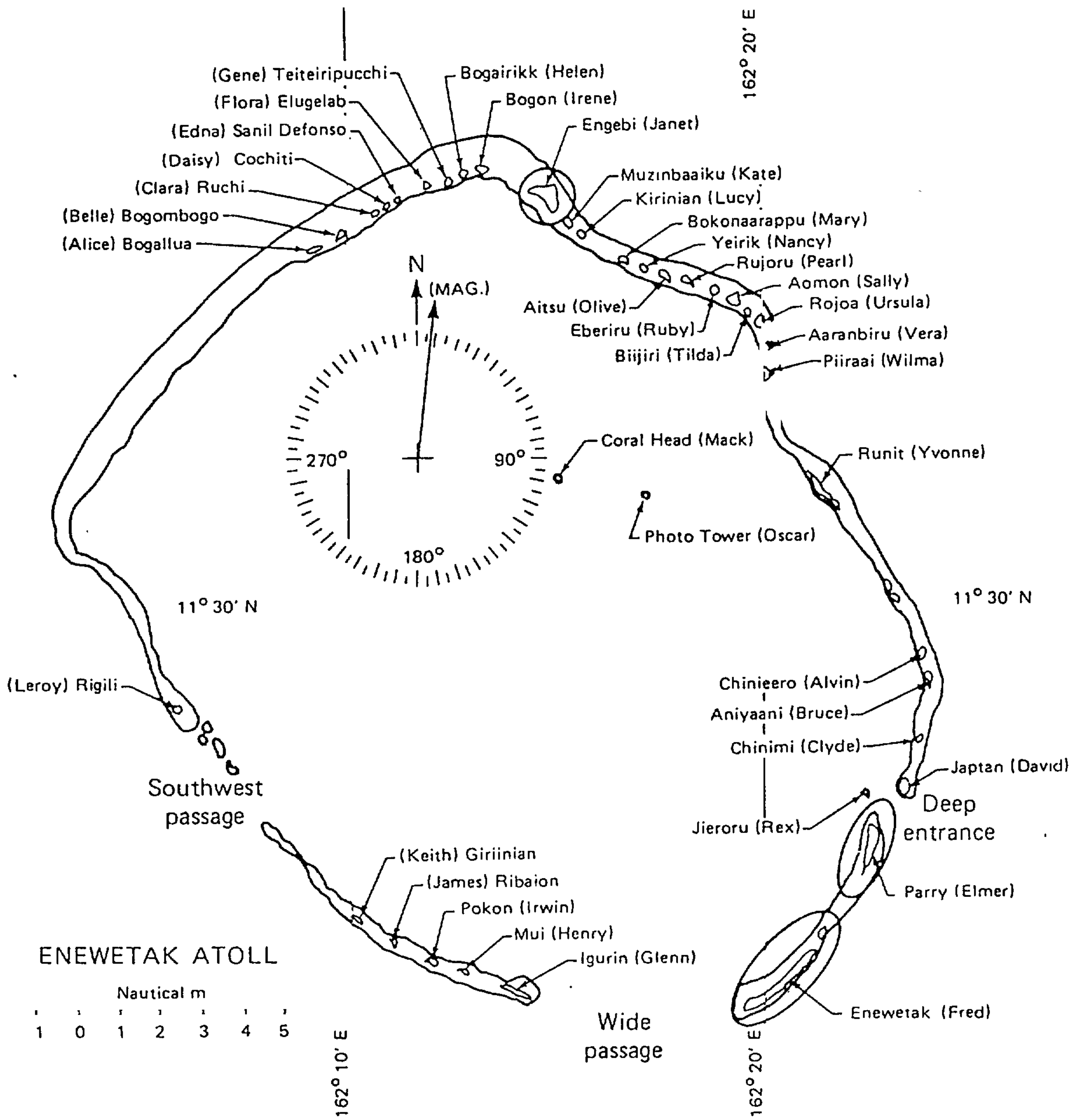

Fig. 5. Map of Enewetak Atoll.

Atoll were based upon these assessments.

The availability of this assessment of Bikini and Eneu Islands at Bikini Atoll allows comparison of the predicted doses at the two atolls. These predicted doses are, of course, based upon assumptions on the time sequence of availability of key food products as outlined in the respective assessments. The predicted dose for the living pattern using Bikini Island for residence and agricultural products exceeds any predicted for Enewetak,

Table 34. Thirty-yr integral dose comparisons of living patterns for Bikini and Enewetak Atolls.[a]

Living patterns and location	Whole body, rem	Bone marrow, rem	Federal guidelines for population average WB[b] and bone marrow, rem
Bikini pattern 1 — Eneu Island	4.2	5.8	5
Bikini pattern 6 — Bikini Island	28	42	5
Enewetak pattern 3[c] — Engebi Island	9.1	13	5
Enewetak pattern 1[c] — Southern Islands	0.22	0.43	5
United States background radiation[d]	3.0	3.0	5

[a]Natural background has been subtracted from the Enewetak and Bikini living patterns.

[b]WB = whole body.

[c]See Enewetak Radiological Survey, Vol. 1 (1973).

[d]Based upon an annual external background dose of 100 mrem/yr at sea level.

primarily because key food products will be available much sooner and the external gamma doses are higher.

The doses predicted for the primary living patterns at the two atolls are listed in Table 34. The highest predicted doses occur for the living pattern involving Bikini Island, Pattern 6, at Bikini Atoll. The integral 30-yr whole body and bone marrow doses are 28 and 42 rem, respectively. The predicted doses are approximately 2.5 times higher than those predicted for Engebi Island at Enewetak Atoll (whole body, 11 rem; bone marrow, 16 rem), which is the living pattern leading to the second highest predicted doses at the atolls. Eneu Island, Pattern 1, at Bikini Atoll ranks third in the list of four major living patterns at the two atolls. The whole body dose of 4.2 rem and bone marrow dose of 5.8 rem for Eneu are approximately one-half those predicted for Engebi Island at Enewetak Atoll. However the Eneu doses are about five times higher than the southern island living patterns at Enewetak, which lead to the lowest predicted doses of all living patterns at either atoll (whole body, 1.0 rem; bone marrow, 1.2 rem) and are in fact lower than U.S. doses.

Bone doses in the Enewetak Radiological Survey[1] were calculated for mineral bone. These mineral bone doses were compared to the Federal guideline of 3 rem/yr for a member of the population. The doses in this report, and in the AEC Task group Report[37] for Enewetak Atoll were calculated for bone marrow and are compared to the Federal guideline of

0.5 rem/yr for a member of the population. The bone doses listed for Enewetak Atoll in the Enewetak Radiological Survey Report[1] were converted to bone marrow doses and included in Table 34 to allow comparison with doses from Bikini Atoll.

The Federal guidelines for whole body and bone marrow are listed in the last column of Table 34 for comparison with the predicted doses for each of the major living patterns at the two atolls. Doses predicted for Bikini Island and Engebi Island exceed the guidelines, while the Eneu living pattern is very marginal. The use of the southern half of Enewetak Atoll leads to predicted doses below the federal guidelines, and, again, are lower than in the United States (see Table 34).

In final analysis it appears that for living patterns with diets composed of locally grown products and residence on the larger islands at Bikini Atoll, which are more suitable for residence (i.e., Bikini and Eneu Islands), no living pattern is possible that leads to as low a dose as is possible at Enewetak in the southern half of that atoll. Preliminary data[8] from the only other large island at Bikini Atoll, i.e., Namu, indicate that predicted doses for this island are more similar to those predicted for Bikini Island.

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Technical Director
1975 Bikini Survey

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EXTERNAL DOSE ESTIMATES FOR FUTURE BIKINI ATOLL INHABITANTS

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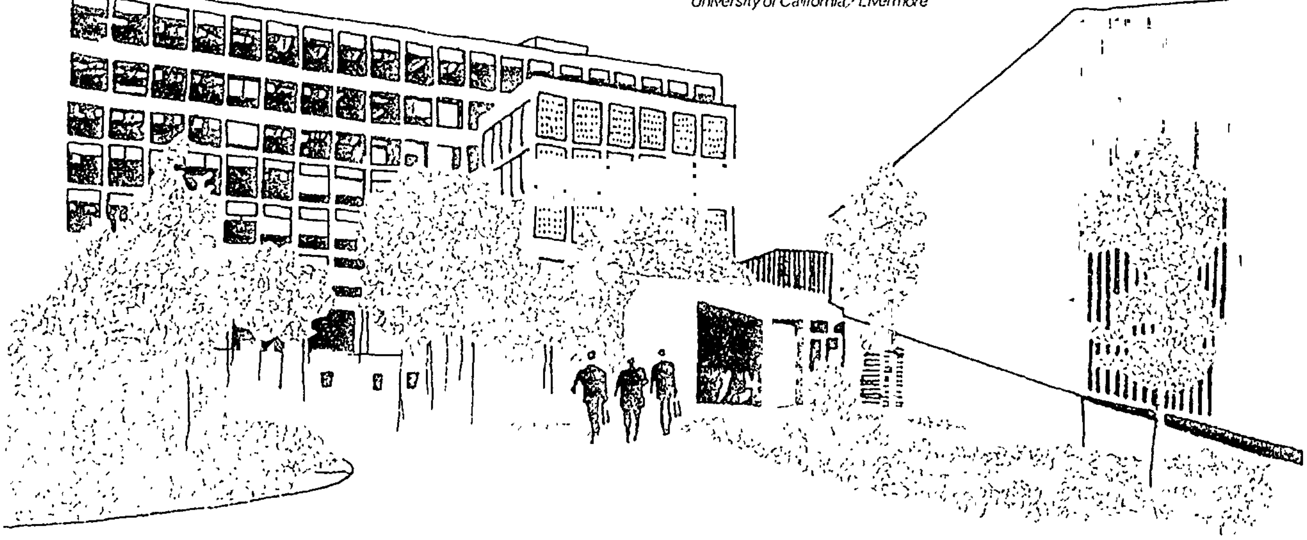

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